Transverse Spin

This section summarizes progress by experiment and theory on transverse spin physics at RHIC, identifies the key questions to be addressed, and defines a plan for the future.

The goal of the RHIC spin program is to identify how the proton gets its spin from its quark and gluon constituents. Addressing this goal when the proton spin and momentum vectors are orthogonal is of great interest since windows onto partonic orbital motion are available, and the proton gets no contribution from gluon polarization when its spin is transverse to its momentum. Transverse single spin asymmetries (SSA) play a special role in questions about the transverse spin structure of the proton because only very small transverse SSA are expected in the scattering of gluons and quarks mediated by gauge interactions, particularly for the light up and down valence quarks of the proton. Consequently, extensions beyond the simple collinear, leading-twist perturbative QCD (pQCD) picture of hard scattering are required, since strikingly large spin effects are observed at RHIC energies where cross sections are found to be in agreement with theoretical expectations.

Extensions to the simplest hard-scattering picture fall into two broad categories, both of which make contact with fundamental questions about the transverse spin structure of the proton. In the Sivers mechanism [1], one requirement to produce a transverse SSA is the presence of a spin-correlated transverse momentum in the distribution functions associated with the proton. The presence of partonic transverse momentum within the proton is related to its orbital motion, albeit in a model-dependent way. In the Collins mechanism [2], transversely polarized quarks must be present in a transversely polarized proton. This transverse quark polarization is given by transversity [3], a leading-twist distribution function whose integral provides the tensor charge of the proton. In the Collins mechanism, quark transverse polarization is revealed following the hard scattering by a spin-correlated transverse momentum in fragmentation to the observed hadrons. Transverse quark polarization can also be revealed by a chiral-odd fragmentation function, such as the interference fragmentation function [4].

Transverse SSA effects are observed to be strikingly large by experiments at RHIC energies [5,6], but their understanding is in general quite subtle and involves substantial theoretical effort to quantify. The concurrent progress between theory and experiment has identified a clear path to test present understanding.

Present Status of Experiments and Theoretical Understanding

RHIC run 6 provided a wealth of experimental information about spin physics. The versatility of RHIC was demonstrated by spending a portion of the run with transversely polarized colliding beams, and the majority of the run with longitudinally polarized colliding beams, for both $\sqrt{s}$ = 62 and 200 GeV collision energies. Transversely polarized proton collisions resulted in the observation of strikingly large spin effects for forward $\pi^0,\pi^\pm$ production (Fig. 1) [5,6]. At large Feynman-x (x_F), positive asymmetries are observed for π^+ production and negative asymmetries for π^- production, consistent with opposite signs for u and d quarks extracted for Sivers functions in phenomenological fits to semi-inclusive deep inelastic scattering (SIDIS) data [7,8]. The π^0 asymmetries are positive due to *u*-quark dominance. What is special about making these

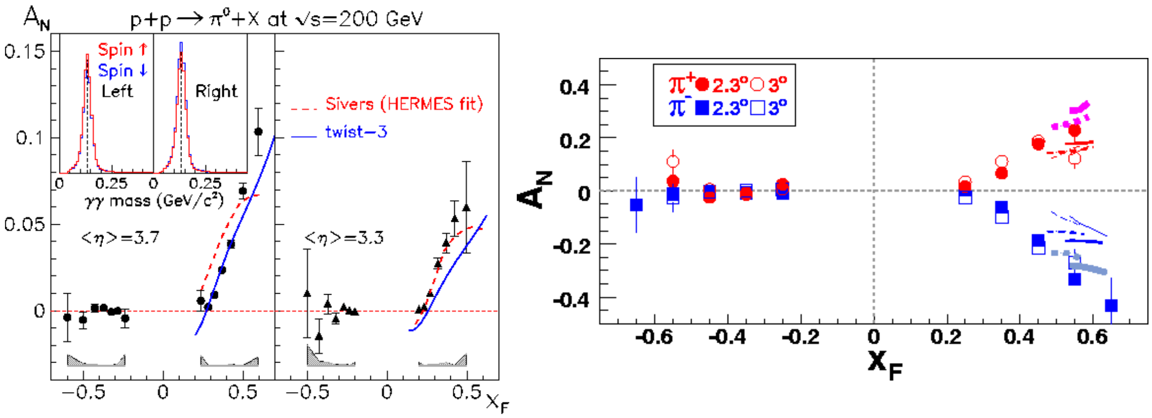

Fig. 1 Transverse single spin asymmetries (SSA) in x_F bins for forward π production at RHIC energies. (left) π^0 production for $\sqrt{s}$ = 200 GeV collisions, at two different pseudorapidities [5]. (right) $\pi^\pm$ production for $\sqrt{s}$ = 62 GeV collisions, at two different scattering angles [6]. The x_F>0 dependence of the measured transverse SSA is mostly consistent with new theoretical calculations described below.

measurements at RHIC energies, is that unpolarized cross sections in the same kinematics as the observed transverse SSA are described by next-to-leading order (NLO) pQCD calculations, and have been shown to help constrain fragmentation functions in a global QCD analysis [9]. This is quite different from the situation at lower collision energies, where measured cross sections exceed NLO pQCD expectations by progressively larger factors as $\sqrt{s}$ decreases.

The calculations in Fig. 1 are an outgrowth of intense theoretical activity concurrent with the ongoing experiments. The principal findings of the theoretical work are summarized here. Calculations that employ spin- and transverse-momentum dependent distribution functions (Sivers functions) and calculations that explicitly treat higher twist effects [10,11] have been found to be equivalent over part of the kinematics for Drell Yan production of dileptons [12]. The Sivers functions have been found to be related to partonic orbital motion in model dependent analyses [13]. Although rigorous proofs of their more general use remain to be found, model calculations[14] using Sivers functions extracted from SIDIS measurements can explain most features of the x_F dependence of the forward pion results at RHIC (Fig. 1). As discussed in more detail in the appendix, first measurements of the p_T dependence of transverse SSA for p↑+p → π + X at RHIC energies, suggest that the understanding of these spin effects is still incomplete.

Very recent work [15] suggests that contributions from the Collins mechanism, where a spin dependent fragmentation function analyzes the scattered quark polarization, are not negligible in p↑+p→p+X. Recent work by a RIKEN/BNL Center group has resulted in the first experimental observation of spin dependent fragmentation in e^+e^- collisions [16]. The Collins function is found to be large. An analysis has been completed, combining the experimentally determined Collins function from e^+e^- and Collins moments from SIDIS, to make the first extraction of transversity [17]. It remains a task for RHIC experiments, and theory, to identify a method to quantitatively separate Collins and Sivers contributions to transverse SSA in p↑+p collisions, so as to establish the universality properties of transversity and the Collins fragmentation function.

First measurements of transverse SSA for di-jet production near midrapidity were also completed in RHIC run 6 [18], with the intent of directly measuring the spin dependence of the transverse momentum imbalance between the jets [19]. Transverse SSA for midrapidity dijet production is found to be consistent with zero. Theoretical understanding of the complex color-charge interactions that arise in di-jet production was stimulated by these results. A synopsis of that understanding is that the Sivers functions are probed in different ways in different hard scattering processes. For semi-inclusive deep inelastic scattering, there is an *attractive final-state color charge* interaction required by gauge invariance, and provides the required amplitude interference in the Sivers mechanism [20]. For the Drell-Yan process, this becomes a *repulsive initial-state color charge* interaction [21]. For di-jet production, both attractive and repulsive color charge interactions are present resulting in cancellations that explain the null result from experiment. An outgrowth of this understanding is the theoretical prediction [22] that for forward photon + jet, repulsive initial-state color-charge interactions will predominate, meaning that transverse SSA for a future RHIC experiment should be opposite in sign from what has been measured in SIDIS. Direct photon production has contributions only from the Sivers mechanism.

The RHIC experiments have both completed forward calorimeter upgrades. STAR built a forward meson spectrometer (FMS) spanning the full azimuth for the pseudorapidity range $2.5 < \eta < 4.0$. The FMS addition provides STAR with nearly contiguous electromagnetic calorimetry for $-1 < \eta < 4$. PHENIX constructed muon piston calorimeters at both positive and negative pseudorapidity that span the full azimuth for $3.1 < |\eta| < 3.9$. The experiments can use these forward calorimeters, in addition to midrapidity detectors for away-side jet detection, to test the prediction that spin-correlated momentum imbalance for forward photon+jet will be opposite in sign to the Sivers asymmetry measured in SIDIS.

A key issue that must be addressed is the discrimination of direct photons from fragmentation photons. It is expected that spin effects for prompt photons will be severely diluted unless robust discrimination against fragmentation photons is made [11]. The large acceptance of the recently completed forward calorimeters at STAR and PHENIX should allow effective application of isolation cuts for this purpose, but it remains important to experimentally demonstrate that fragmentation photon backgrounds can be adequately suppressed.

Key Questions for the Future

Future studies of transversely polarized proton collisions at RHIC will address key questions listed below.

- Is the present understanding of the Sivers mechanism correct?

Experimental confirmation of the theoretically predicted sign change is a tremendous future opportunity for RHIC. Transverse SSA for Drell-Yan (DY) production of dilepton pairs is the cleanest test of this prediction, but will require luminosity development and upgrades to the

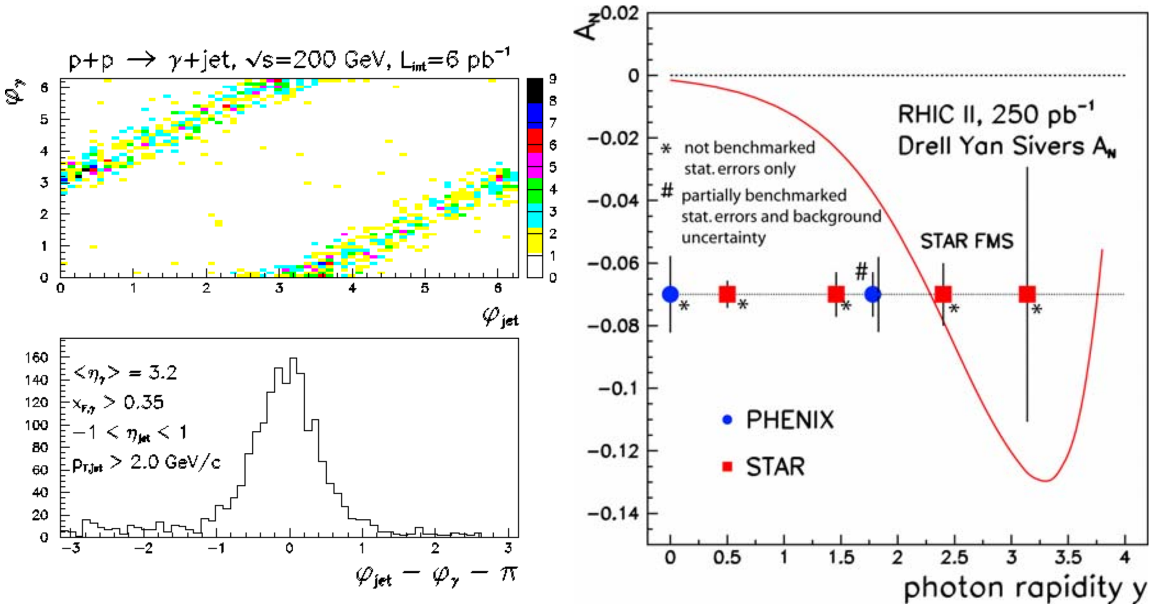

Fig. 2 Tests of the Sivers mechanism through measurement of transverse single spin asymmetries for (*left*) forward photon + jet final states. The signature of repulsive color charge interactions would be a negative asymmetry for the spin-correlated momentum imbalance, related to the $\Delta\phi = \phi_{jet} - \phi_{\gamma} - \pi$ simulations. (*right*) Transverse single spin asymmetries for Drell-Yan production of dilepton pairs at $\sqrt{s}$=200 GeV [23].

experiments. As documented in [23] and based on detailed comparison of data to simulation, PHENIX will need to suppress contributions from weak decays of open beauty and open charm production to low mass $\mu^+\mu^-$ pairs to cleanly identify the DY process for a future transverse SSA measurement. It is expected that open heavy flavor contributions can be suppressed by isolation cuts using the planned nose cone calorimeter and the forward vertex tracker upgrades. STAR has the potential for a transverse spin DY experiment by observing e^+e^- pairs at large rapidity with its FMS. Fast tracking at large rapidity is a required addition for STAR to discriminate electrons from positrons. From considerations of both integrated luminosity and the necessary upgrades to the experiments, a transverse spin DY is envisioned for the future.

The predicted sign change is of fundamental importance, not only because it verifies the presence of partonic orbital motion, but also because it establishes the reality of attractive interactions between unlike color charges and repulsive interactions between like color charges. Before embarking on a transverse spin DY program, forward photon + jet can rigorously test present theoretical understanding, since the repulsive color charge interactions are predicted to be present for this rare, but presently accessible, final state.

- Can experimental sensitivity to transversity be established at RHIC?

Probes of transversity at RHIC will necessarily be exploratory, since no firm theoretical predictions exist, at present. Transverse SSA are again expected to play a special role, since two-spin observables such as A_{TT} are predicted to be small at RHIC energies. Single spin asymmetries can provide a window onto transversity either through the Collins mechanism or via the interference fragmentation function. Given that transversity is largest in the valence region, and the Collins function is largest for hadrons that carry large fractions of the momentum of the fragmenting parton, it is expected that the forward region will continue to play a special role. Exploratory studies of spin correlations with the azimuthal orientation of two particles detected in the forward direction can be conducted in parallel with experiments targeted at measuring transverse SSA for forward photon + jet to test the understanding of the Sivers mechanism.

- Are there ways to robustly separate flavor contributions to Sivers functions and to transversity?

The mirror transverse SSA for forward $\pi^{\pm}$ production are consistent with opposite signed contributions to transverse spin effects from up and down quarks. One way to clearly separate flavor contributions is to compare results from proton transverse SSA to those from neutron transverse SSA. The latter would require development of either vector polarized deuteron beams or of polarized ^{3}He beams at RHIC.

Summary and Plan

Future opportunities for transverse spin physics at RHIC are now focused on theoretical predictions based on understanding of SIDIS, $e^{+}e^{-}$ and RHIC results. Experiments to test this understanding include near-term opportunities, for which both accelerator performance and experiment readiness is complete. There are longer term opportunities, with time and resources required to prepare for future measurements of transverse spin effects in the production of rare final states. When both near-term and future opportunities are realized, these targeted data sets that will address specific theoretical predictions can also be used for more exploratory studies, for example to identify a means of robustly separating Collins and Sivers contributions.

A key future goal is to quantitatively test the prediction that initial-state repulsive color charge interactions provide the amplitude interference required by the Sivers mechanism for $p\uparrow + p$. The cleanest test of this is for Drell Yan production of dilepton pairs. Considerations of the kinematics and luminosity suggest that $\sqrt{s} = 200$ GeV p+p collisions optimizes the opportunity for both PHENIX and STAR to complete the measurement, at parton momentum fractions that emphasize valence quarks. Continued luminosity development at RHIC for polarized proton operation is required to produce the 250 pb^{-1} data sample required for the measurements. Targeted upgrades to the experiments can be embarked upon during the execution of the W physics program, to prepare the experiments for measurements in 2015 and 2016.

The sign change between what has been observed in SIDIS and what is predicted for transverse spin DY tests a fundamental aspect of QCD, since unlike color charges are responsible for the final-state attractive interaction in SIDIS, and like color charges are predicted to give exactly the opposite sign Sivers effect in the p+p DY production.

Theoretical understanding of the Sivers mechanism can be subjected to an experimental test prior to embarking on a transverse spin DY measurement. In particular, continuing commitment of a fraction of RHIC spin runs to transversely polarized collisions is required to complete measurements of transverse SSA for forward photon + jet, with sufficient precision to establish the sign of the spin asymmetries. The optimal plan would be to obtain a data sample of 6 pb^{-1}

with 65% polarization in RHIC run 9 to establish that robust discrimination between direct and fragmentation photons can be made. Completion of the measurement is estimated to require a total sample of 30 pb^{-1} with 65% polarization and is envisioned for a subsequent RHIC run, prior to the start of the 500-GeV program. Concurrent with these targeted measurements, more exploratory measurements aimed at identifying transversity contributions can be embarked upon.

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